

Dark Matter versus Modified Newtonian Dynamics

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June 6, 2008

Abstract

Analysis of orbiting stars local to the Milky Way have given rotation curves for our galaxy that flatten out with increasing distance, contrary to rotation curves of the solar system as predicted by Newtonian gravity.

The leading explanation for the shape of the rotation curves is due to a substance deemed Dark Matter that interacts only gravitationally. Another theory, named Modified Newtonian Dynamics, seeks to explain Dark Matter as an anomaly from our understanding of gravity. In this paper, we examine the evidence for both Dark Matter and Modified Newtonian Dynamics to determine which is a more plausible explanation for the observed rotation curves.

1 Origin of Dark Matter

Detailing the origin of Dark Matter (DM) requires a trip back into history. Early in the 20th century, astronomer Fritz Zwicky analyzed the Coma Cluster of galaxies and found that there was far more mass than easily seen in the visible spectrum, given the speeds of the galaxies in the cluster.[1] This is where the term, “dark” matter originated from. We cannot see this mass directly, like luminous matter such as stars and galaxies, so it is called “dark” for that reason, having nothing to do with color. Compared with a mass estimate given by analyzing how bright the cluster was, an unexpected result appeared. Comparing the speeds of the galaxies in the cluster to the estimated mass, Zwicky found that upwards of 400 times the mass of the luminous galaxies was accelerating the galaxies in the Coma Cluster to the observed speeds.

In the late 1950’s and early 1960’s, further studies on spiral galaxies showed that their rotation curves did not obey the currently held model of Newtonian gravity.[2] The science of astronomy during this tumultuous period became even further muddled by new observations of local stellar velocities. In the Milky Way, like the observed galaxy clusters, stars on the edge of the gravitational influence of the galaxy still orbit at about the same velocity as those closer in.

Why this is a problem can be brought to light by example. In the solar system, planets closer to the center of mass (the Sun) orbit around it quicker than their counterparts further out. This is in direct accordance with Newton’s law of gravity, $F = \frac{GMm}{r^2}$, where M and m are the respective masses involved and r is the distance. We see that the further out an object is, like Saturn or Pluto, the less force due to gravity the object experiences. Less force means less acceleration, as given by another of Newton’s laws $F = ma$. So to have so much speed due to acceleration in galaxy clusters, or stars in a galaxy, it is akin to thinking that the Sun would have to have a lot more mass in order to pull Pluto hard enough for its orbital period to be about a year: standard orbiting time for the Earth.

Yet this would require a new model of the solar system. The Sun dominates the local gravitation close in, but to have Pluto orbit in 1 year would require a spherical distribution of matter

much larger than the sun that interacts only gravitationally on the outer planets, effectively ignoring the orbits of the inner planets. This is how the model of the Milky Way galaxy is built up currently: that a spherical halo of DM exists around the Milky Way, accelerating the outer stars to a higher orbital velocity.

2 Observational Evidence for Dark Matter

The observational evidence for DM stemmed from large-scale surveys to shorter and shorter-distance scales. One of the greatest tests of DM was the discovery of gravitational lensing by large galaxy clusters. This provides an independent means of showing that a large amount of matter exists, despite surveys of luminous matter.[3] A product of Einstein's theory of General Relativity, mass warps space and, consequently, light beams traveling close to this warped space will bend. The amount of curvature can be determined by the amount of mass and gives us a different way of finding the mass of a galaxy cluster that does not rely on the speeds of the individual galaxies. The conclusion is the same, however: that much more mass is responsible for the bending of light around galaxy clusters, than available via luminous matter alone.

One of the most striking examples of DM observation is that of the Bullet Cluster.[4] Two large galaxy clusters collided to form a structure separate of its constituent luminous matter and intergalactic dust. Data showed that the gravitational wells of the two colliding clusters were not where they were first thought to have been located. Usually associated with luminous matter (or the hot gas between the galaxies), the gravitational wells of the Bullet Cluster were far from any matter at all. Large amounts of gravitational force, corresponding with no detectable matter became direct proof of dark matter's existence.

Perhaps the best evidence for DM is that of observed abundances of deuterium observed today. Deuterium is simply a hydrogen atom (a proton and an electron) with a neutron bound to the proton. In cosmology, deuterium abundances set very tight constraints on baryonic matter densities in the current universe. Baryonic matter is the matter that we are familiar with in everyday life: protons, neutrons and so on. The observed amount of deuterium suggests that only a few percent of the universe is made up of normal protons and neutrons. Current cosmological models point to matter densities ranging about 25 - 30 percent of the universe. If only a few percent of the total mass density of the universe is familiar matter, then we have yet another strong backing for the existence of missing matter.

The future of DM observation is rich, as well. Questions governing the intrinsic properties of DM, pertaining to composition, local distribution and so on are actively being pursued.[5] The future study of DM is astoundingly important. The energy density of the universe is principally dark energy, with the matter density part of that largely made up of dark matter. With stars, galaxies, planets and humans making up only a minute few percent of the entire universe, exploring the nature of DM is exploring into the nature of the building blocks of the universe. A whole new universe of experience lies in our exploration of the unknown, delving deep into the dark of space on an investigative mission of cosmic proportion. To understand more about the universe is to understand more about ourselves, because we are, all of us, a part of the universe itself.

3 The Rise of Modified Newtonian Dynamics

Modified Newtonian Dynamics (MOND) was first proposed in the early 1980s to solve the question of Dark Matter. Prior to the evidence listed above, questions arose about whether or not our fundamental understanding of Newton's law of gravitation was actually correct. The

mathematics of MOND were derived to accept what we know about how gravity works on the short-distance scales, the scales any normal person is familiar with, and also to comply with the observations of galactic rotation curves.

The theory sought to change the familiar $F = \frac{GMm}{r^2}$ to $\vec{F} = m \cdot \mu\left(\frac{a}{a_0}\right) \vec{a}$. Where

$$\mu(x) = \begin{cases} 1 & |x| \gg 1 \\ x & |x| \ll 1 \end{cases}$$

This changes the force of gravity from a non-linear to a linear force after a certain distance is involved. Familiar Newtonian force is still there, but a new $\mu(x)$ function appears as a ratio of accelerations. The new theory states that gravity works on normal levels for short-distances, as in everyday life. Short distances, in this equation, also extend to scales of solar systems, but below that of galaxies.

A consequence of setting the new force equation equal to that of Newton's and solving for a velocity yields $v = \sqrt[4]{GMa_0}$ with a_0 the new acceleration constant, akin to a constant of velocity in Special Relativity. This explains the flatness of rotation curves at high distances being more or less constant.

A simpler example of how MOND works is how Einstein's theory of Special Relativity works. In it, at low velocities, things are normal, but as soon as we approach speeds close to that of the speed of light, properties like length, mass and time become relatively abnormal. MOND works in a similar fashion, but with force and distance. The distances involved are the underlying factor for the acceleration a and acceleration constant a_0 for cosmological purposes. Normally a is so large on local scales that it vastly overpowers the equation, approximating Newtonian force, going unnoticed.

The development of MOND stemmed from the seemingly ludicrous supposition from the pro-DM camps: the assertion that DM is made up of some sort of special type of matter that cannot be seen, interacted with or examined in any way. With MOND, a mathematical framework is established that allows the more fundamental solving of the missing mass problem with symbols and numbers.

The fact that General Relativity breaks down on quantum scales also begs the question as to whether or not gravity follows the same structure: whether its behavior changes as a function of very large distance, much as its influence does on the very small distances of the atomic realm.

4 Observational Evidence for MOND

Because of the Earth's vicinity to large gravitational fields, producing large accelerations, the effects of MOND were unnoticed until galactic rotation curve data began to pour in, thereby saturating the above equation so that the MOND $\vec{F} \approx F$ from Newtonian gravity. MOND works within the uncertainties in data of rotation curves and currently applies only to large-scale structures.

Observational evidence for MOND is scarce, if evident at all. Because it is a theory that describes what we see already, it makes no predictions for what we should see or any consequences thereof. Whereas DM and rotation curves arose from theories built from basic principles, MOND is constrained to fit observation.

Given its recent development, MOND has yet to establish any groundbreaking scientific discoveries. A recent study of the same Bullet Cluster mentioned before, using MOND, suggests there is no need for DM in that scenario.[6] However, MOND has yet to describe other celestial phenomena that DM has potentially solved, such as structural formation in the early universe.[7]

5 Conclusion

To conclude, while galaxy cluster observations have proposed questions about the nature of DM, observational evidence provides a strong backing. The lensing of light from galaxy clusters is a direct result of General Relativity, which has been incredibly successful at describing the large scale structure of the universe and provides a direct method with which to analyze the amount of DM in a galaxy. Observed deuterium abundances point directly to a large amount of missing matter. Similarly, observations of the displacing of gravitational wells from regular, luminous matter in the Bullet Cluster have virtually nailed shut the question of DM's existence.

And yet with MOND, the same Bullet Cluster data can be shown to exist independent of the presence of DM. While being untestable in the local solar system presents a colossal challenge to accredit the theory, MOND can be put through its paces on the large-scale scene within limits. Experiments are going on now to find the constituent reason as to why DM exists, be it in large hard to see stars in vast quantities, or tiny weakly interacting particles with lots of mass in even more vast quantities.

MOND has no experiments to test if it is valid or not, for it relies only on what we see and not what we get. If there is no way to test MOND's existence independent of looking out beyond the solar system, to see if we can find our misunderstanding of a very basic principle of force dating back to the early 16th century, then MOND has seen the peak of its day and should not be considered a valid candidate for explaining the anomaly of the missing mass in the universe.

Currently, the winning theory is DM by a long shot. With substantial evidence to back it up, from the ground up, DM has many independent ways of being proved, many different applications throughout cosmological history and has the ability to be tested locally on Earth or the Milky Way, despite the difficulty of finding the culprits of the mass distribution.

The world of cosmology in the last half century has been through a cyclone of change and it is without a doubt that in less than another half century, the question of the missing matter in the universe will be solved, and light will finally be shed on Dark Matter.

References

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